HIGH-TEMPERATURE MATERIALS: INTRODUCTORY REMARKS

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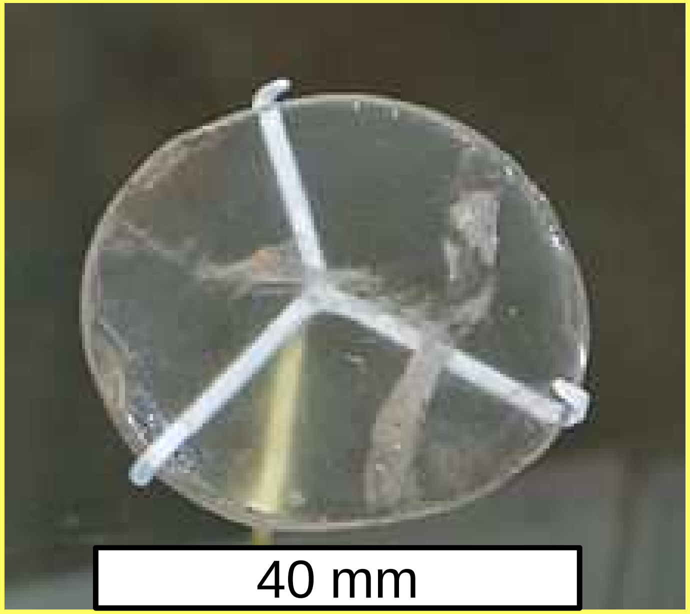
CALENDARIUM

1 800 000 B.C. – appearance of Homo erectus (syn. pitekantrop)
1 000 000 B.C. – control of fire, Wonderwerk cave (Republic of South Africa)
400 000 B.C. – control of fire, Qesem cave (Israel)
200 000 B.C. – appearance of Homo sapiens
1 000 B.C. – lens from Nimrud

Homo erectus

http://humanorigins.si.edu/sites/default/files/styles/full_width/public/images/square/erectus_JC_Recon_Head_CC_f_sq.jpg?itok=9Ppv5SG2



Lens from Nimrud

https://upload.wikimedia.org/wikipedia/commons/thumb/6/65/Nimrud_lens_British_Museum.jpg/220px-Nimrud_lens_British_Museum.jpg

HIGH TEMPERATURE MATERIALS YESTERDAY

Rocks – first high temperature materials

<u>Aplication of fire:</u>

Heating living areas

Frightening animals

Preparation of food

↓

Production of metals and alloys

Production of ceramics

↓

Sophisticated processing methods at high temperatures

Application of materials at extreme thermal conditions

DEFINITIONS

- High temperature material – a material capable of operation above about 1000℉ (540℃).

- High temperature material – a material, which operates above two-thirds of its melting point.

In order to perform successfully and economically at high temperatures, a material must have at least two essential characteristics: it must be strong, since temperature increase tends to reduce strength, and it must exhibit resistance to its environment, since oxidation and corrosion attacks also increase with temperature.

HIGH TEMPERATURE MATERIALS TODAY

- Refractory metals (e.g. Ti, Zr, Nb, Mo, Hf, Ta, W)
- Stainless steels
- Superalloys
- Titanium alloys
- Carbon-carbon composites
- Metal matrix composites
- Advanced ceramics

HIGH TEMPERATURE MATERIALS TODAY - REFRACTORY MATERIALS

This category includes:

- metal elements, e.g.: Ti, Zr, Nb, Mo, Hf, Ta, W
- silicon-based refractory compounds, e.g.: SiC, Si_3N_4, $MoSi_2$, SiO_2

Properties:

- extremely high melting point,
- significant resistance against heat and wear
- good stability against creep deformation
- high hardness at room temperature

Applications of refractory metals include casting molds, wire filaments and utilization in powder metallurgy.

REFRACTORY METALS
- EXAMPLES OF APPLICATION

Filament of a 200 Watt incandescent lightbulb

https://upload.wikimedia.org/wikipedia/commons/0/08/Filament.jpg

REFRACTORY METALS
- EXAMPLES OF APPLICATION

Apollo CSM (Command/Service Module) with its dark rocket nozzle made from Nb-Ti alloy

https://upload.wikimedia.org/wikipedia/commons/thumb/c/c0/Apollo_CSM_lunar_orbit.jpg/1024px-Apollo_CSM_lunar_orbit.jpg

REFRACTORY METALS
- EXAMPLES OF APPLICATION

The Pratt & Whitney F-100 engine uses rhenium-containing second-generation superalloys

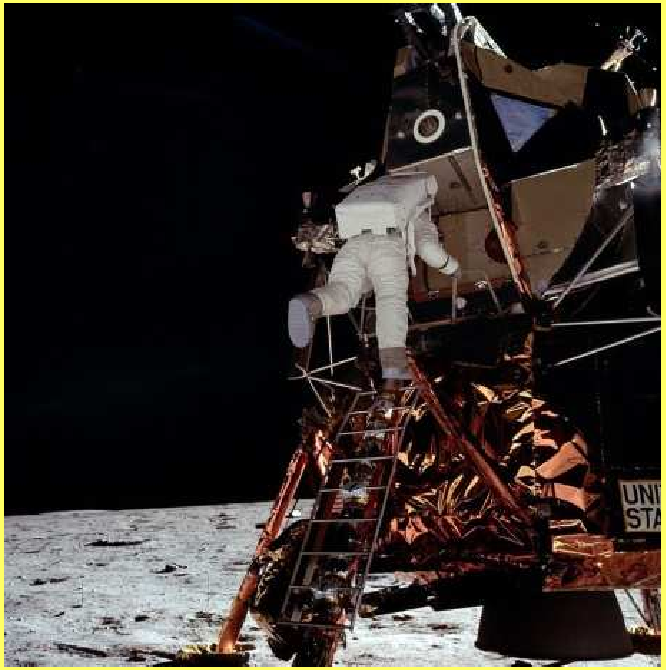
https://en.wikipedia.org/wiki/File:Engine.f15.arp.750pix.jpg

CFM International CFM56 jet engine with blades made with 3% rhenium

https://en.wikipedia.org/wiki/File:CFM56_P1220759.jpg

REFRACTORY METALS
- EXAMPLES OF APPLICATION

Hafnium is used in alloys with iron, titanium, niobium, tantalum, and other metals. An alloy used for liquid rocket thruster nozzles, for example the main engine of the Apollo Lunar Modules, is C103 which consists of 89% niobium, 10% hafnium and 1% titanium.



Hafnium-containing rocket nozzle of the Apollo Lunar Module
in the lower right corner

https://upload.wikimedia.org/wikipedia/commons/thumb/4/4e/Apollo_AS11-40-5866.jpg/220px-Apollo_AS11-40-5866.jpg

HIGH TEMPERATURE MATERIALS TODAY - STAINLESS STEELS

Stainless steel, also known as inox steel or inox – from French *inoxydable* (inoxidizable) – is a steel alloy with a minimum of 10.5% chromium weight content.

Stainless steels are used when both the properties of steel and corrosion resistance are required. Stainless steels contain sufficient chromium to undergo passivation, forming an inert film of chromium oxide on the surface. This layer prevents further corrosion by blocking oxygen diffusion to the steel surface and stops corrosion from spreading into the bulk of the metal.

Stainless steels are used in cookware, cutlery, household hardware, surgical instruments, major appliances, industrial equipments and as automotive and aerospace structural alloys, as well as construction materials in large buildings.

HIGH TEMPERATURE MATERIALS TODAY - SUPERALLOYS

Superalloys, also known as high-performance alloys, are materials with excellent mechanical strength and creep-resistance, good surface stability, as well as oxidation resistance at high temperatures. Oxidation resistance is provided by elements such as aluminium and chromium.

Examples of superalloys (registered trademarks):

- Hastelloy, consisting of 22 different nickel-based (+ Mo, Cr, Co, Fe Cu, Mn, Ti, Zr, Al, C, W) corrosion resistant alloys. Application: corrosive environments, chemical reactors, nuclear reactors.
- Inconel, based on Ni and Cr.
- Waspaloy, consisting of nickel-based alloys that maintain their room temperature strength to about 1000 ^{o}C. Application: gas turbines
- Rene alloys, consisting of nickel-based alloys that maintain their room temperature strength to about 1000 ^{o}C. Application: jet engine and missile components, outer shell of space capsule.

HIGH TEMPERATURE MATERIALS TODAY - TITANIUM ALLOYS

Titanium alloys are materials that contain a mixture of titanium and other chemical elements. Such alloys have very high tensile strength and toughness even at extreme temperatures. They are light in weight, have extraordinary corrosion resistance and the ability to withstand extreme temperatures. However, the high cost of both raw materials and processing limit their use in military applications, aircraft, spacecraft, medical devices, highly stressed components, such as connecting rods on expensive sports cars, as well as some premium sports equipment and consumer electronics.

HIGH TEMPERATURE MATERIALS TODAY
- CARBON-CARBON COMPOSITES

Carbon fiber-reinforced carbon (s.c. carbon-carbon) composite is an effective high-temperature material for structural applications.

Advantages:

- high thermal shock resistance
- low coefficient of thermal expansion
- thermal protection
- lightweight
- good strength retention up to 1400 ^{o}C

Disadvantages:

- low impact resistance
- significant oxidation rate at temperatures higher than 500 ^{o}C, demanding application of coatings, e.g. sealers (not effective at HT), SiC and HfC (T = 2200 ^{o}C).

HIGH TEMPERATURE MATERIALS TODAY - CARBON-CARBON COMPOSITES, continued

Applications:

- structures of high-speed flight vehicles, e.g. the nose leading edge, horizontal control surfaces, tail leading edge
- aircraft brakes
- high-temperature bearings and clutches
- nozzles
- heat shields

HIGH TEMPERATURE MATERIALS TODAY
- CARBON-CARBON COMPOSITES, continued

Thermal soak aerodynamic heat shield used on a Space Shuttle

https://upload.wikimedia.org/wikipedia/commons/thumb/e/e2/Discovery%27s_heat_shield.jpg/1024px-Discovery%27s_heat_shield.jpg

HIGH TEMPERATURE MATERIALS TODAY
- CARBON-CARBON COMPOSITES, continued

Apollo 12 capsule's ablative heat shield (after use)

https://upload.wikimedia.org/wikipedia/commons/thumb/f/f2/Apollo_12_heat_shield.JPG/1280px-Apollo_12_heat_shield.JPG

HIGH TEMPERATURE MATERIALS TODAY - METAL MATRIX COMPOSITES

A **metal matrix composite** (**MMC**) is a composite material with at least two constituent parts, one being a metal as a requisite, the other material may be a different metal or another material, such as a ceramic or organic compound. When at least three materials are present, it is called a **hybrid composite**. An MMC is complementary to a cermet.

Applications:

- cutting tools are made from a tough cobalt matrix cementing hard tungsten carbide particles
- tank armors may be made from metal matrix composites, e.g. steel reinforced with boron nitride
- automotive disc brakes
- rotors of sport cars (Porsche) are made from carbon fiber within a silicon carbide matrix because of its high specific heat and thermal conductivity
- structural components of a jet's landing gear (F-16 Fighting Falcon) are made from silicon carbide fibers in a titanium matrix

HIGH TEMPERATURE MATERIALS TODAY - ADVANCED CERAMICS

Carbon-silicon carbide ceramic matrix composite
Ceramic composites (borides, carbides, nitrides)

A PICA (phenolic impregnated carbon ablator) is a lightweight ceramic ablator that was designed in the 1990s to burn away slowly and in a controlled maner. It has very low density (20% of conventional heat shields) and can withstand temperatures up to 1930 ^{o}C.

NONDESTRUCTIVE EVALUATION METHODS OF HIGH-TEMPERATURE MATERIALS

A critical part of assuring the ability of high-temperature materials to sustain the operating conditions for which they are designed is their integrity, material quality and property consistency with the design requirements. The detection of defect and the characterization of properties without affecting the integrity of the material or structure require the use of non-destructive testing methods:

- in-service non-destructive monitoring
- ultrasonics
- liguid penetrants
- radiography
- thermography
- visual inspection
- eddy-current testing
- laser interferometry

GENERAL EXAMPLES OF HIGH TEMPERATURE MATERIALS APPLICATION

1. Operating underground and at great Earth depths:
   - geothermal energy
   - oil and gas exploration
   - underground mining
   - underground steam pipes
2. Space exploration of hot planets in the solar system
3. Superfast flights
4. Electronics
5. Others:
   - engines
   - metallurgy
   - coal power plants
   - cutting tools
   - military, etc.

OPERATING UNDERGROUND AND AT GREAT EARTH DEPTHS

TABLE 17.1

Temperature at the Various Layers of Earth

Layer/Depth	Temperature (°C)
Crust—0–100 km thick	Up to about 500
Upper mantle—down to 1000 km	~500–900
Mantle (dense, hot layer of semisolid rock)—1000–2900 km	~1200
Outer core—2900–5100 km (liquid/magma)	~000
Inner core—5100–6378 km (solid)	>5000

Source: Based on the USGS website "Inside the Earth" http://pubs.usgs.gov/gip/dynamic/inside.html.

Y. Bar-Cohen, High Temperature Materials and Mechanisms. CRC Press, Boca Raton, USA, 2014.

Remarks:

- Temperature gradient at the Earth surface layer: 20-25 ^{o}C/ km
- 20% of geothermal energy originates from the period of planet formation, while 80 % is the result of ongoing radioactive mineral decay

HTM FOR GEOTHERMAL ENERGY

Application of geothermal energy:

- direct utilization in district heating systems
- generation of hot water
- production of electricity

Problems:

- temperature of about 350 ^{o}C
- high cost of deep drilling in areas of hot rocks
- difficulties in placing and controlling the curing time of the cement used to create a borehole casing at high temperatures
- presence of highly corrosive fluids

Potential problems:

- generation of earthquakeke and volcanic eruptions
- influence on Earth's magnetic field
- thermal death of the planet

HTM FOR EXPLORATION OF HOT PLANETS IN THE SOLAR SYSTEM

Problems:

- high temperatures of surface (Mercury from -173 to 427^{o}C, Venus about 460 ^{o}C)
- aggressive atmosphere of Venus
- high pressure of Venus atmosphere
- elongation of duration of missions (more than 2 hours)

Techniques used to slow the destructive effect of heating landers:

- application of strong thermal insulation
- application of phase-change heat sink materials

HTM FOR SUPERFAST FLIGHTS

Problems:

- high flying speed which causes temperature growth
- growth of vibrations
- oxidation

Speed regimes:

- supersonic (1-2.5 Mach) – combat planes
- hypersonic (5-10 Mach) – represents the latest challenge in developing aerodynamic systems for military aircrafts
- high-hypersonic (10-25 Mach) – reentry speed into Earth’s atmosphere. Heat shields based on such materials as carbon/carbon composites are necessary.

HTM FOR ELECTRONICS

<u>Problems generating by elevated temperature</u>:

- melting point of the solders (180^{o}C for soft solders, 400^{o}C for hard solders)
- the practical upper limit of commercially available circuits (300^{o}C)
- SiC-based semiconductors (600^{o}C)

In order to ensure the service life of military devices, military standards define the requirements for the design and testing limits (MIL-STD-810).

TABLE 17.2

Typical Automotive Maximum Temperature Ranges

Automobile Part	Temperature Range
On the engine and in the transmission	150–200°C
On the wheel sensors	150–250°C
Cylinder	200–300°C
Exhaust	Ambient 300°C and can reach as high as 850°C

Y. Bar-Cohen, High Temperature Materials and Mechanisms. CRC Press, Boca Raton, USA, 2014.

THE END